Autonomous Rehabilitation and Maintenance of Natural Gas Pipes

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Team Members: UIUC (Professors Nancy Sottos, Jeff Moore and Paul Braun), CMU (Professor Howie Choset), Redion Services (Robert Ragland)

Project Vision

We are developing a rehabilitation system for natural gas pipes that will result in a structurally and functionally independent pipe within an existing legacy pipe. The pipe material will will resist damage mechanisms envisioned. The system will take advantage of embedded self-healing and self-reporting agents, which will arrest damage and prevent further propagation and highlight damage areas for more extensive maintenance, respectively.

Total Project Cost:	$5.56M
Length	36 mo.

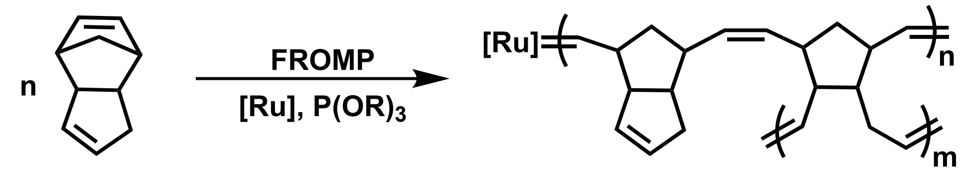
Project Objectives & Approach

- Develop a rehabilitation solution for natural gas at a cost of < $1MM/mile

OBJECTIVES	PROPOSED APPROACH
New Pipe; Structurally and Functionally Independent of Original Pipe	Extruded-in-Place Pipe-in-Pipe System (ExiPiP™); Leverage FROMP of DCPD
Rehabilitation Material with Mechanical Properties Supporting 50-Year Life	Leverage Mechanical Properties of FROMP-Cured Poly(DCPD)
New Rehabilitation Incorporating Smart Features	Screen well-evaluated self-healing and self-reporting chemistries for integration into the poly(DCPD) pipe
Remote/Robotic Deployment and Inspection	Development of Novel extrusion nozzle and robotic tools for pipe inspection, and new pipe deployment

Concept

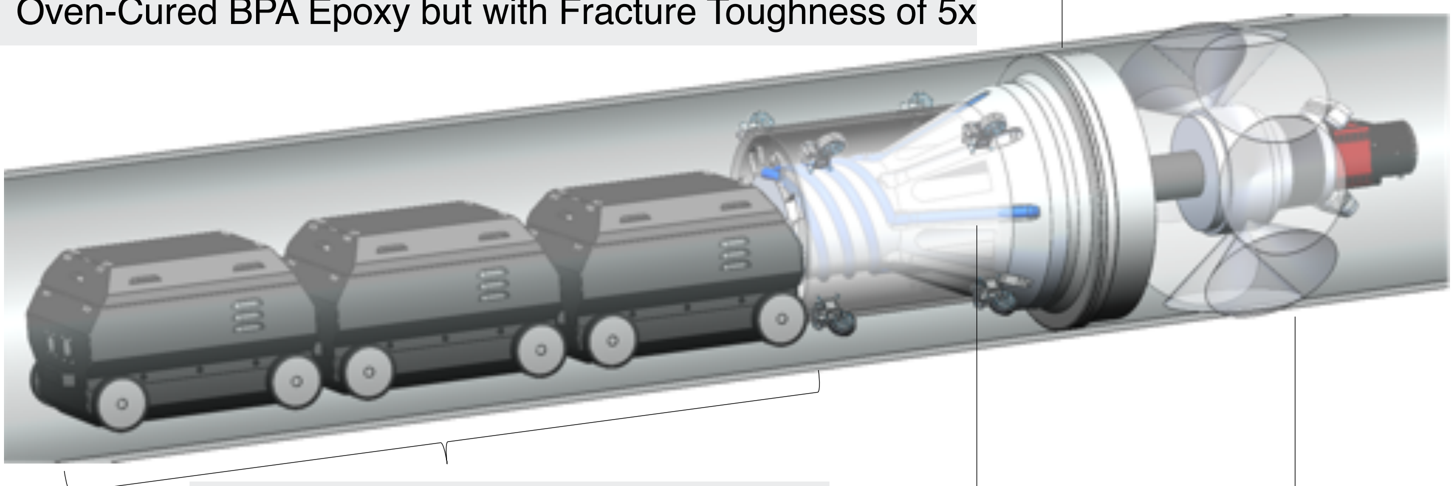
uncured liquid monomer → solid polymer



Dicyclopentadiene

Poly(dicyclopentadiene)

Extrusion Nozzle with Heating Element to Initiate Cross-linking of DCPD; Poly (DCPD) exhibits Modulus and Tensile Strength Comparable to Oven-Cured BPA Epoxy but with Fracture Toughness of 5x



Drive robot and functional modules

Monomer/Catalyst Blend Feed to Extrusion Head

Visual, thermal and UV sensors for assessing rehabilitation feasibility, degree of cure of new pipe and ongoing integrity management

Team Responsibilities

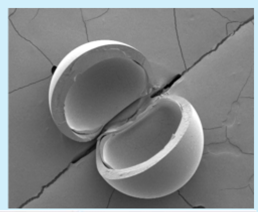
Category 2 Smart Materials Coating Development (UIUC + AMI)

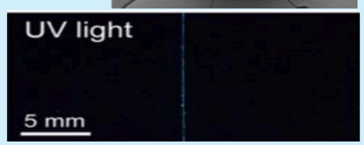
- **Develop Extruded-in Place Material**
  - > Frontal curing of DCPD inside a pipe
  - > Optimize resin formulation
  - > Modify rheology for nozzle extrusion
  - > Characterize properties

- **Develop Smart Additive Solutions for Self-Healing and Self-Reporting**
  - > Microencapsulation of healing & reporting agents
  - > Environmental stability
  - > Formulation scale up
  - > Performance assessment

nozzle

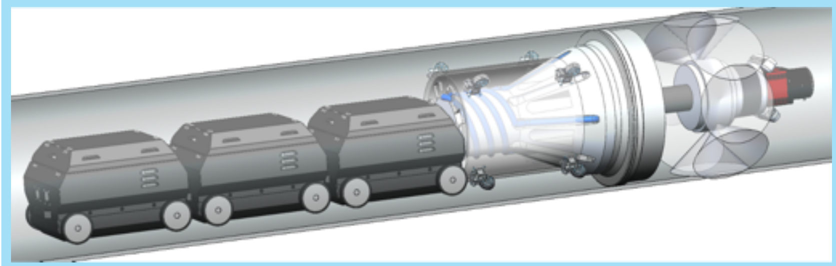
cure front





Category 3 Coating Deposition Tool Development (CMU)

- **Cable Laying Robot**
  - > Thread cable and perform go/no-go inspection
- **Coating Deposition Robot**
  - > Material deposition nozzle (with UIUC)
  - > Material management



Category 4 Pre- and Post-Inspection Tool Development (CMU)

- **Pre-Inspection and Post-Inspection Robots**
  - > Post-installation pipe property characterization
  - > Post-deployment UV light/camera module
  - > Algorithms to process/analyze sensor readings

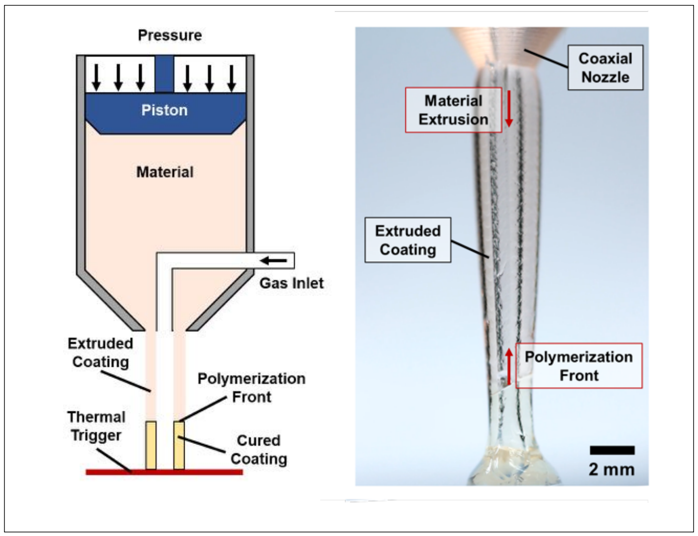
Category 5 Integrated Solution Testing (AMI + Redion + GTI)

- **Review Best Practices**
- **Work Safety and Environmental Risk Review**
- **Preliminary Field Trials**

arpa·e CHANGING WHAT'S POSSIBLE

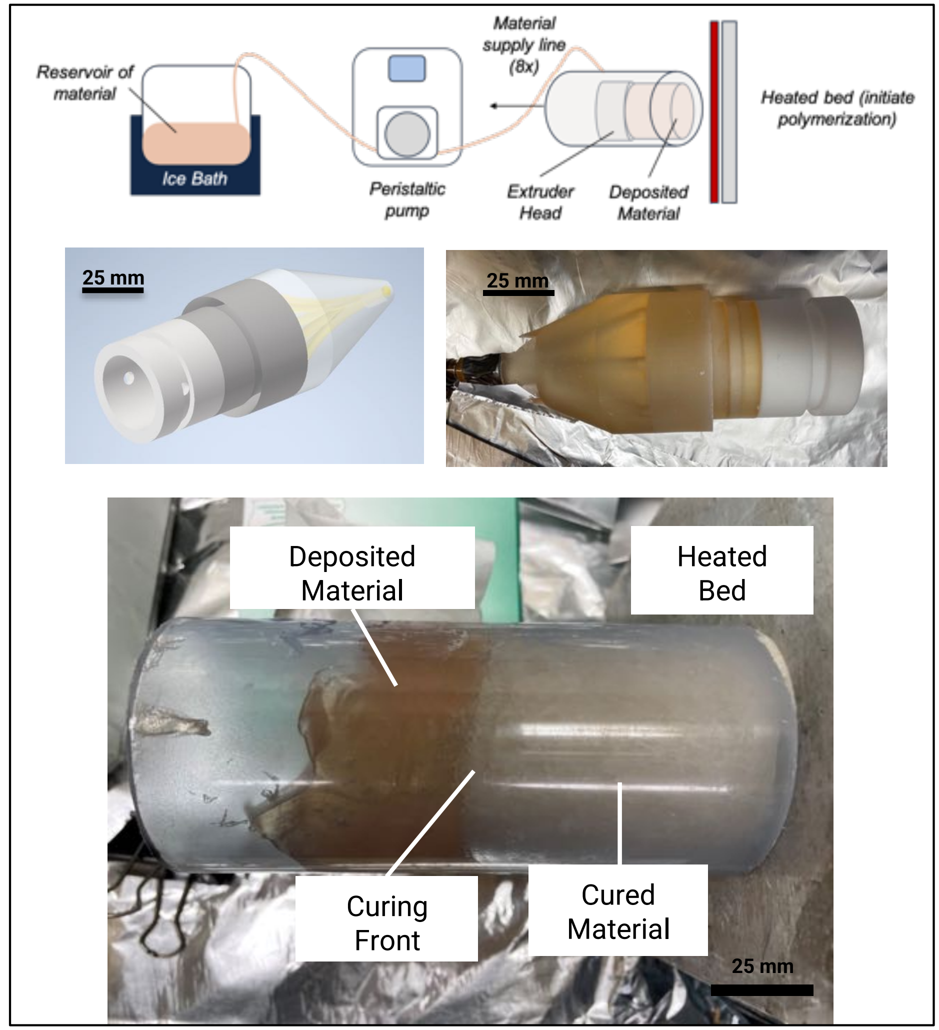
Extrusion, Nozzle Design and Scale Up

Original Lab-Scale Deposition Nozzle



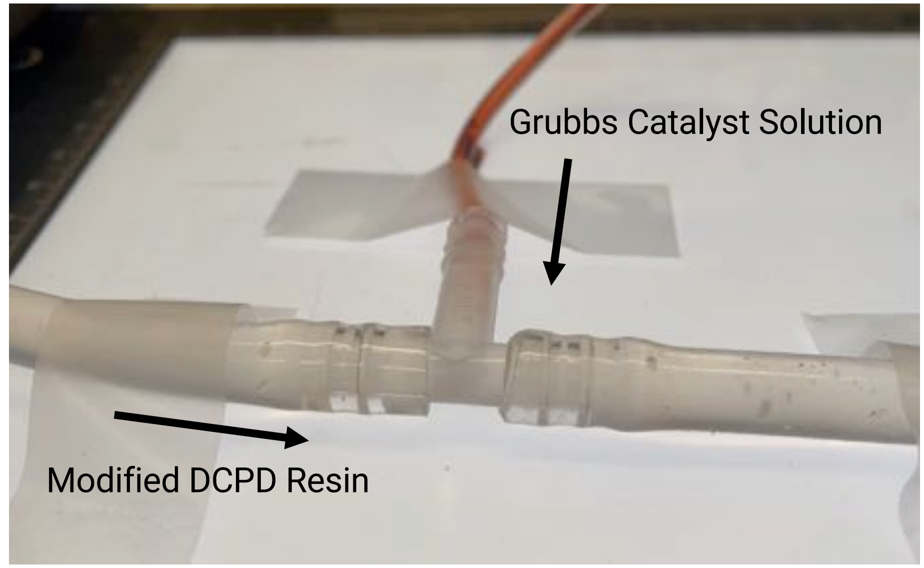
~25x Scale increase

Intermediate Scale Deposition Nozzle



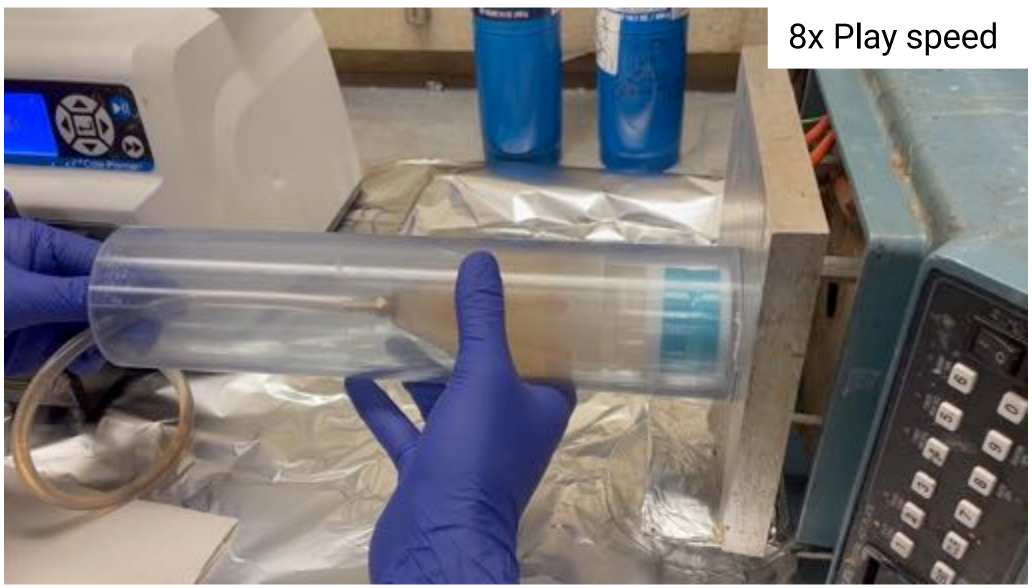
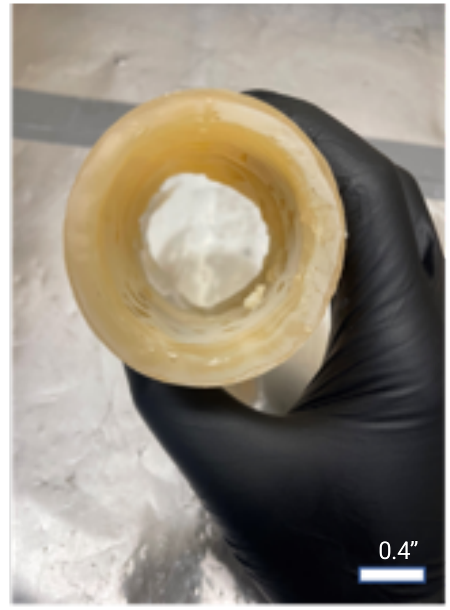
Intermediate Scale mixing of resin and catalyst

- On-the-fly mixing of two components - ease storage, delivery, and deployment of resin system
- Modified resin and catalyst can be mixed together using a static inline mixer close to extruder head
- Next steps - increase the scale of delivery using gear pumps and integration with robotic systems



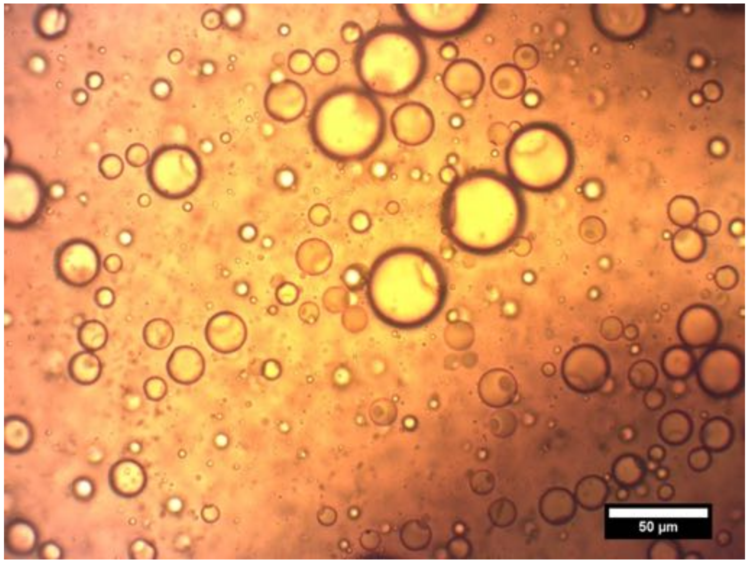
Intermediate Scale Extrusion Trials

- Base resin: Dicyclopentadiene (DCPD) and 2nd generation Grubbs Catalyst (G2)
- Scale-Up: 2mm batch print to 12” continuous extrusion
- Resin system modified to increase viscosity from ~10cP to ~4000cP to allow for better sag resistance and forming
- Further modification with chemical inhibitors to greatly increase working time
- Modified resin and catalyst system has been successfully extruded to target pipe wall thickness of 0.2” (0.51cm) inside of a 2.5” PVC pipe
- Next Steps - Extruding at 12” diameter and integration with robotic systems

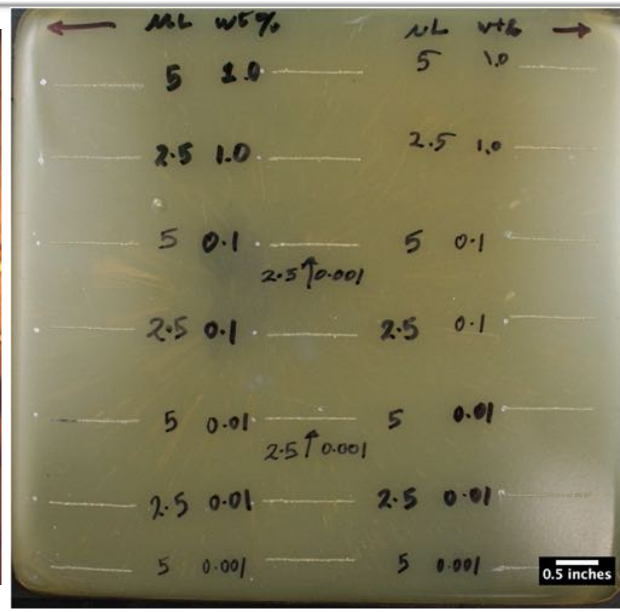



8x Play speed

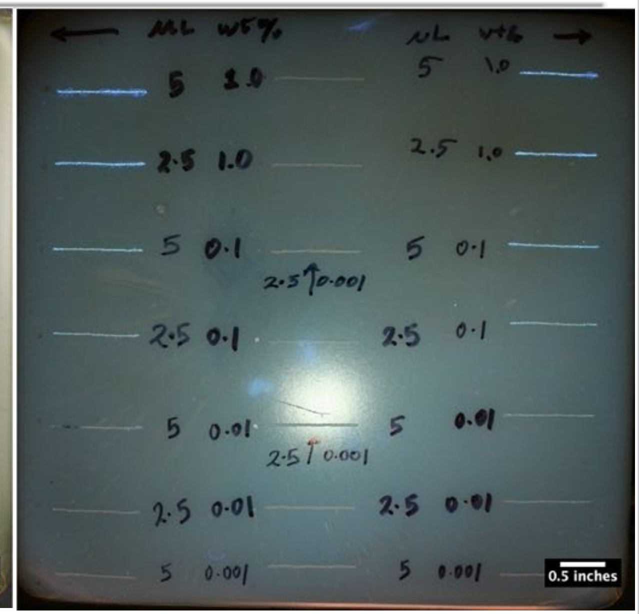
Self-Healing and Self-Reporting



Encapsulated DCPD



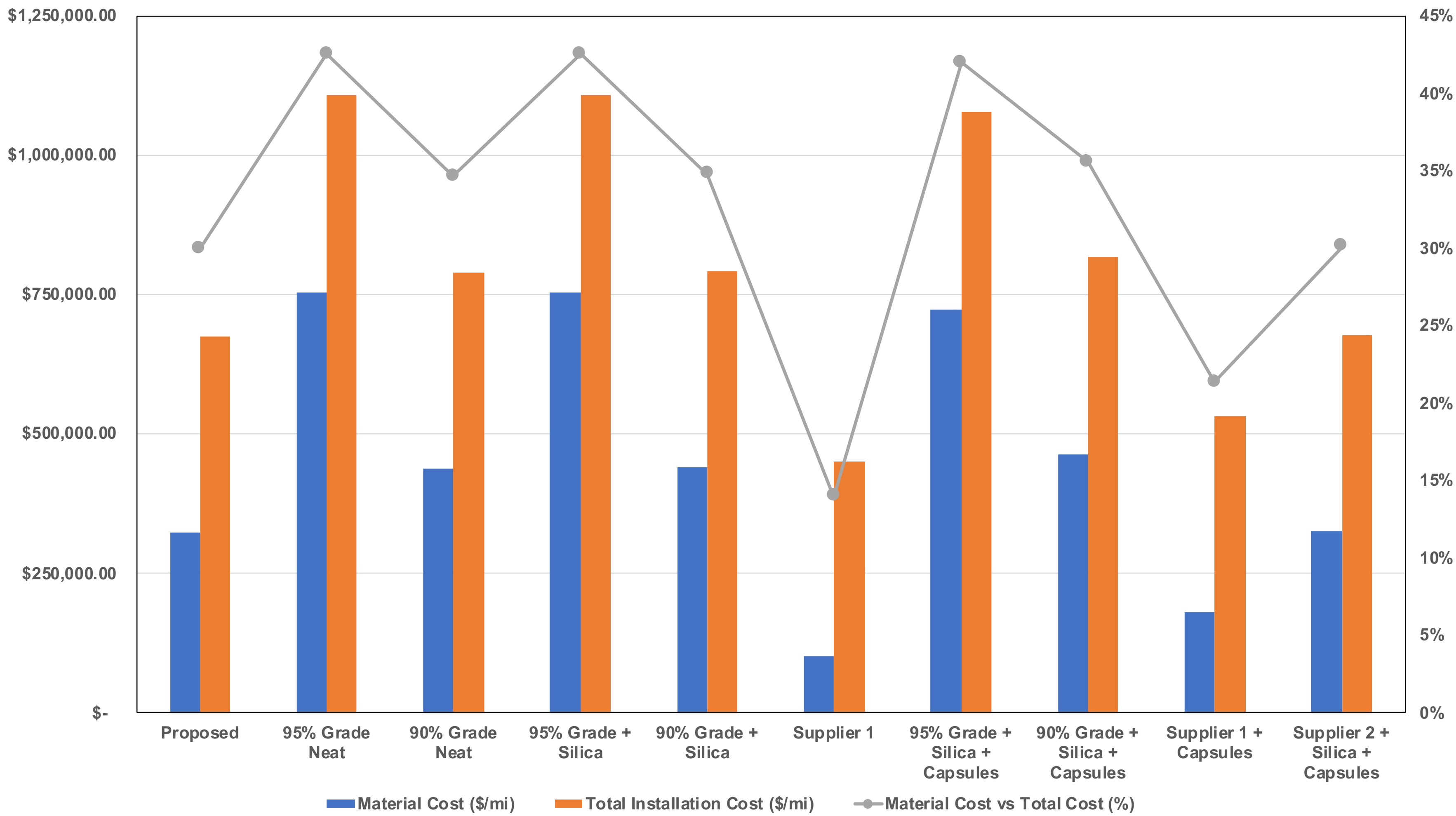
Damage with reporting material under Florescent lighting



Damage with reporting material under 365nm UV light

- Self-healing: Healing Agents have been encapsulated and initial Reference TDCB testing shows up to 70% healing efficiency
- Self-Reporting: Material encapsulated and proof of concept demonstrated in poly(DCPD) Matrix

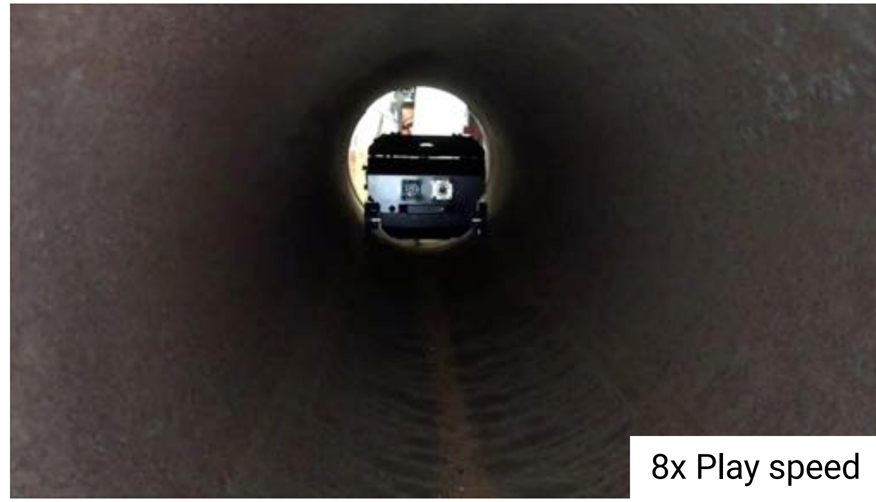
Scaleup and Sourcing Considerations



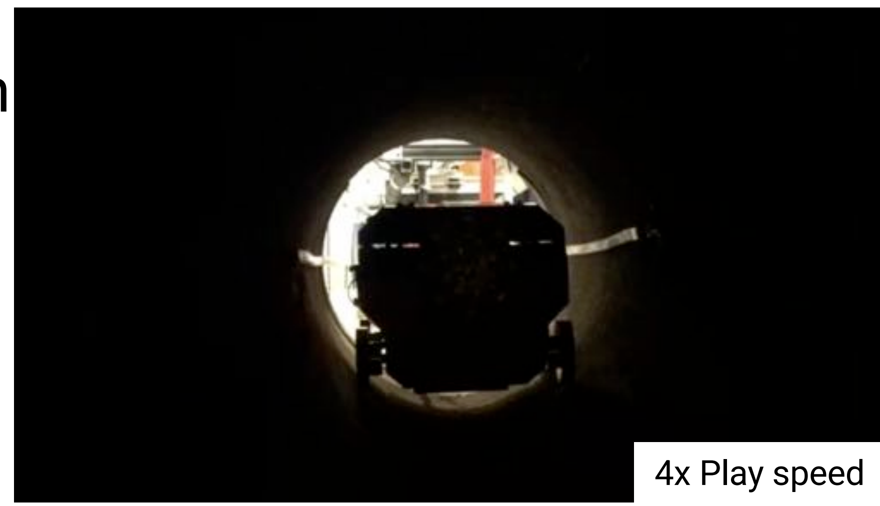
- Monomer purity an important factor in FROMP Kinetics. Sourcing and evaluation efforts ensured compliance with costing goals

POC Robot Year 1 Summary

- Completed POC robot
  - Accomplishments
    - Finished drivetrain design
    - Finished first unit assembly
    - Tested robot in pipe (video 1)
- Next Steps
  - Sensor controlled movement with POC robot platform (video 2)
  - Develop final version robot in parallel



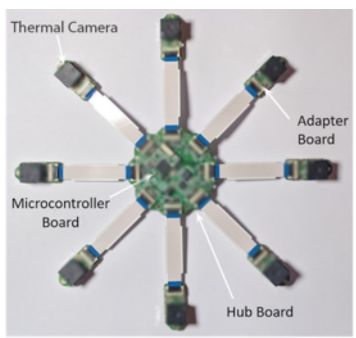
8x Play speed



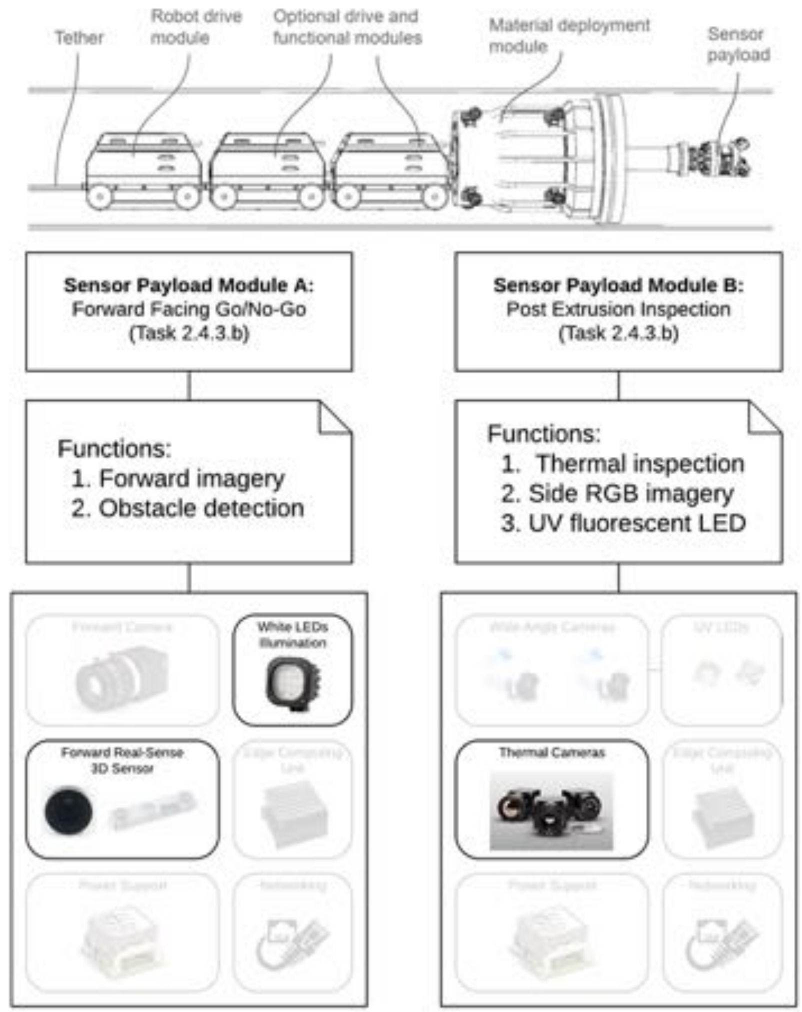
4x Play speed

Sensor Payload Summary

- Completed sensor design including:
  - Module A - Forward facing Go/No-Go
    - Front facing camera
  - Module B - Post extrusion inspection
    - Side facing camera
    - Thermal sensor
    - UV inspection sensor
- Next step:
  - Sensor guided tasks



Sensor board fabricated



Challenges and Risks

Technical

- Reaction kinetics and effect on pipe extrusion rate and control
- Broad set of levers including monomer types and mix ratios, catalyst types and loadings curing temperatures to manage risk
- Understanding the effects of scale on nozzle design

Organizational

- Program design anticipated more face-to-face and hands-on collaboration (essential in a large group with multiple collaborators)
- Requires intentional and deliberate organizational structure to facilitate project management
- Generally leading to a challenge with our deliverable timetables

Supply Chain

- Delays in acquiring key materials and components

Talent

- Some turnover in team and recruiting new personnel is increasingly challenging

Potential Partnerships

Mapping Capabilities

- Combination of ExiPiP™ Rehabilitation system with mapping module developed by CMU will lead to a more complete solution

Surface Preparation and Installation Experience

- Partners with more insights on installation conditions

Contact:

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Summary

- Our Extruded-in-Place Pipe-in-Pipe (ExiPiP^{TM}) solution will allow for the installation of a new structurally independent pipe without the need for excavation
- The pipe material will be highly resistant to damage but will incorporate self-healing and self reporting functionality in the event of damage
- Follow-on phase/program:
  - Extensive field testing and refinement; broad scope of application development engagements to develop ExiPiP^{TM} platform tunability – engaging regional partners for alternative funding sources
- Team Acknowledgements: